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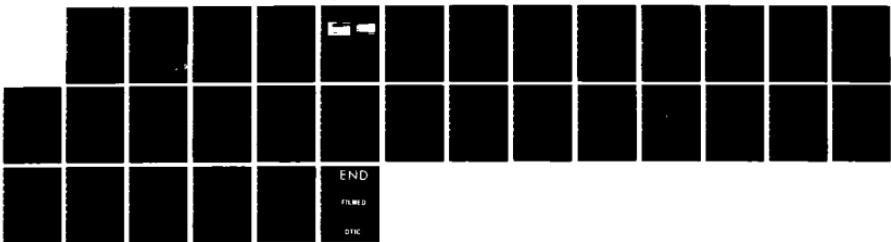
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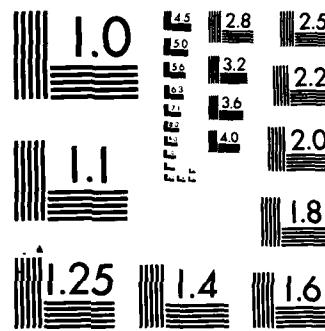
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**CAVITATION INCEPTION**

**Final Report**

**Contract: N0014-75-C-0378**

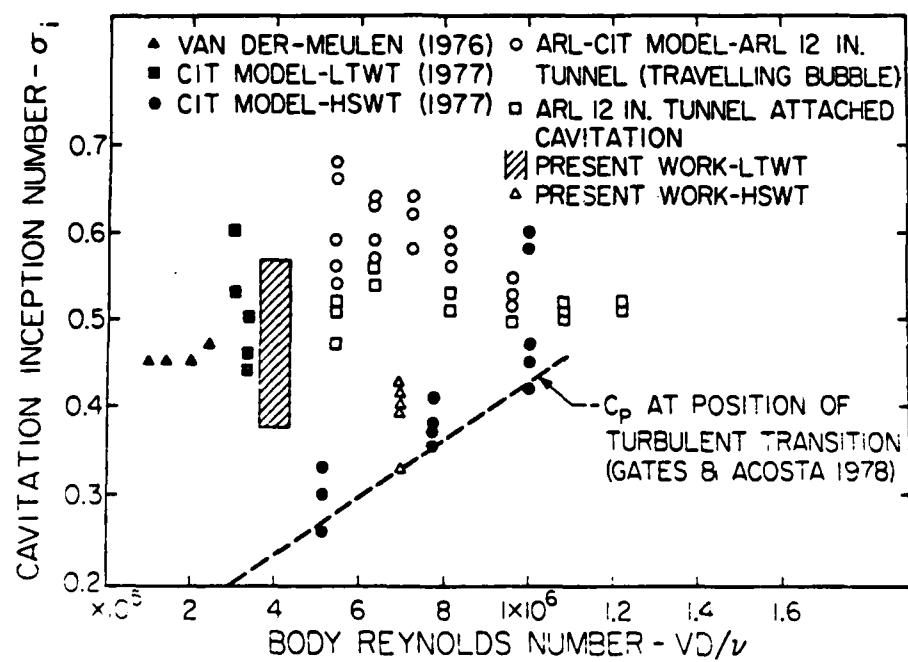
**to**

**David W. Taylor Naval Ship Research  
and Development Center  
Bethesda, Maryland 20034**

**Prepared by**

**A. J. Acosta  
California Institute of Technology  
Division of Engineering and Applied Science  
Pasadena, CA 91125**

**March 1985  
Report E 183.7**



Cavitation inception on the non-separating "Schiebe" head form  $C_{p\min} = -0.75$  showing large experimental scale effects and different kinds of cavitation

## 1. Introduction

This report summarizes in brief research on Cavitation Inception from the period 1 October 1974 to 30 September 1984 carried out under the General Hydrodynamic Research program of the David W. Taylor Naval Ship Research and Development Center. This work has been concerned with the onset or "inception" of cavitation on flows past smooth bodies (first) and then bluff bodies with a pronounced separated wake. This work has been entirely experimental as carefully controlled and documented experiments seemed to be quite lacking. Experimenters in this field generally have tended to make certain physical presumptions of the behavior and growth of the cavitation nuclei which lead to cavitation inception without actually observing carefully the process itself. Thus it was and it continues today that cavitation is primarily an experimental subject because of the complex flow environment in which it takes place and because of the dynamic character of the phase change itself which is cavitation inception. The state of understanding now as compared to ten years ago is considerably improved; this improvement lies both in a better understanding of the liquid flow field and of the role that microbubbles and microparticulates play in inception. Cavitation inception research is actively pursued in this country, Europe and Japan; we would like to think that through our research supported by the GHR program that we have contributed usefully to the progress of the last 10 years in the field.

In what follows we itemize the publications, reports and theses produced under the present contract and the graduate research students, research fellows and visiting associates that have contributed their work.

## 2. Personnel

Professors A. J. Acosta and R. H. Sabersky served as Principal Investigators. During the time period E. M. Gates, J. Katz, K. K. Ooi, T. J. O'Hern and L. d'Agostino were all doctoral students in mechanical engineering. In addition E. M. Gates served as a "Visiting Associate" \* to the project during the month of July 1978, after receiving the Ph.D. degree in that year and for the period September 1978 through August 1980 thereafter. Professor Katz received his Ph.D. degree in 1982; he served as a postdoctoral Research Fellow from January 1982 through December of that year and has remained as a Visiting Associate since that time. K. K. Ooi received his Ph.D. degree also in 1982 and messrs O'Hern and d'Agostino continue their research programs. In the meantime Dr. Gates has become Associate Professor of Mechanical Engineering at the University of Alberta and Dr. Katz is an Assistant Professor of Civil Engineering at the University of Purdue. Dr. Katz is the recipient of a "Young Investigators Presidential Award" for the year starting 1985.

In addition Dr. Daniel Oldenziel of the Delft Hydraulic Laboratory was a Visiting Associate from November 1979 through January 1981; Dr. Oldenziel was active in the effects of roughness on Cavitation Inception. Finally, we has occasional visits from Professor V. H. Arakeri formerly supported here at Caltech under GHR support prior to the start of the current contract. Dr. Arakeri is now an Associate Professor at the Indian Institute of Science, Bangalore India.

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\* A faculty appointment at Caltech who may or may not serve with remuneration

### 3. Publications and Reports

The chronological listing of the reports and publications originated all or in part under the aegis of the present contract are included in Appendix 1. At contract expiration students O'Hern and d'Agostino were deeply involved in their experimental research with Mr. O'Hern making double-pulsed holograms of regions of cavitating wake flow and Mr. d'Agostino completing the physical design of the Cavitation Susceptability Meter. These efforts, we anticipate, will be brought to completion in the near future with other means of support. A physical description and drawings of the d'Agostino CSM are contained in the Appendix 2 for completeness.

### 4. Discussion

The problem presented to the research worker in cavitation is well illustrated in the frontispiece; there inception observations on a non-separating headform with a minimum pressure coefficient of -0.75 are collected from several laboratories and several workers. Two different types of cavitation are seen, attached cavitation forming an irregular patch and travelling bubble cavitation. There is a marked inception scale effect since if there were none, inception would occur at the index value of 0.75 on this figure. None of the data shown occur at this value; all are below. It has become plain that the occurrence of these two types of cavitation on this particular kind of test body depends greatly on the concentrations of free stream microbubbles or at least "nuclei" which can support only a small amount of tension before growth into cavitation. The travelling bubble cavitation seen on the right hand photograph is the more readily understood form because then the fairly simple and straight forward mechanics of isolated bubble growth in

a pressure field give some rationale for cavitation scaling processes. But this kind of "single effect" approach is bound to lead to failure for it fails to consider all forms of attached cavitation an example of which is shown on the left photograph of the frontispiece. In fact, the form and appearance of such "attached" cavities on smooth bodies cannot year be predicted in advance for liquids that have a "small" concentration of nuclei susceptible to cavitation.

The present research effort has been concerned with almost all these aspects of the cavitation inception problem; for convenience we lump these into the two categories; the "fluid flow" environment one, and the "liquid" environment, two. By the fluid flow environment is meant the details of the surface static pressure distribution, the real fluid flow features, i.e., whether the flow is separated or not, the boundary layer laminar or turbulent, the characteristics of the unsteady pressure field and the structure of the mixing regions of any wakes or shear flows (insofar as these may affect cavitation). The "liquid environment" refers to the presence of the "nuclei" which give rise to the initiation of cavitation. These nucleating origins can occur on the surface or within the free stream. And in the liquid stream these nuclei can consist of microbubbles (air and water vapor) or solid particles. Solid particles unless they contain pores of undissolved gas are usually not good nucleating sources; most laboratory facilities (water tunnels and towing tanks) contain an abundant amount of such materials. The open sea, however, contains a rich collection of biota consisting both of zoo and phytoplankton (thereby containing metabolic gases) as well as other organic and inorganic debris. This "environment" clearly can not be duplicated in the laboratory and so there has remained a gap in our application of laboratory

research to the ocean itself that is now only gradually and in other contexts being addressed.

The sensitivity of cavitation to nuclei concentration has led the cavitation community generally to the realization that cavitation "nuclei" must be monitored and measured. More than that, where possible these nuclei should be classified as to type. This is easy for the case of microbubbles larger than about 10 micrometers but it is more difficult (but not impossible) to discriminate bubbles from particles for sizes smaller than this. It is another matter, however, to tell if microparticulates as opposed to microbubbles serve as nuclei for cavitation. All of these considerations have led us in the present research effort to develop laboratory means of observing microparticulates and cavitating microbubbles in cavitating flow fields based on pulsed ruby holography. This development is described in Refs. 5,6,7,9,16 and the latter is particularly interesting because if a density contrast is made possible by injection of water with a temperature difference of only 2 to 3 °F, the resulting holograms can be reconstructed as schlieren pictures. At the same time the "gap" referred to above can be partly filled through the agency of the Cavitation Susceptability Meter developed originally by Oldenziel and Lecoffre; in the present case, however, an extension of their work, we believe, will make it possible to quantify the concentration of nuclei causing cavitation and with concurrent use of the holocamera, the fraction of microparticulates that can serve as nucleating sources may be determined. This development is sketched in Ref.24 and a further description of the system is provided in Appendix 2.

Although vitally important to cavitation as the nuclei issue is, the flow field environment has occupied most of our research effort over past years as

indeed it has for the entire research community. These "scaling" issues are described in Ref.1 as of about a decade ago. The influence of the real fluid boundary layer flow on cavitation was the subject of a long series of studies; viz. Refs. 2,3,4 and 6. In the latter the interesting observation was made that on test bodies not normally subject to a laminar separation, the presence of sufficient microbubbles in the incipient stages of cavitation could sufficiently alter the pressure distribution so as to cause a laminar separation.

The effect of turbulent transition appears to be an important feature for cavitation as a number of workers including ourselves have found. Reference 8 reports on these in more detail on the first such IUTAM conference on that subject. Many of these kinds of details are contained in Ref.10, the 4th David W. Taylor Lecture series, and a sort of summary of these viscous effects on smooth bodies is presented in Ref.11. Surface roughness is an important characteristic for any flow and the influence of this feature on cavitation can be important although as the recent literature shows its use to forestall cavitation scale effect is not entirely without controversy. Our own contribution to this subject under the present contract is limited to Ref.15.

All of these kinds of issues, real fluid effects on cavitation past smooth and roughened test bodies and propellers has continued to be of vital concern to practical problems of cavitation testing and there is no doubt that fundamental work will continue in this area. But less ideal flows are also common in the naval hydrodynamic context and these are shear flows. Shear flows are a component in jet propulsion, the large scale separation regions of lifting surfaces and bodies, rearward facing steps and tip clearance flows in propulsors. We have chosen to study two such flows for their importance to cavitation; these are jet flows and massive separated flows past a bluff body.

As a preliminary comment, all of these flows exhibit a strong "apparent" Reynolds number effect on cavitation inception. "Apparent" is used here because it is not yet quite clear that mere geometric scaling with say nuclei concentration is the important parameter. It is also true that the fluid flow environment of the highly unsteady pressure field in the mixing regions of these massive separations is largely not known. We have engaged in a series of test observations, surface pressure measurements and have devised a new concept of "Lagrangian" pressure measurement to contribute new insight into these problems in Refs. 17,18,19,21,22, and 26. This last publication, to our knowledge shows for the first time the emergence of true microbubbles into macroscopic cavitation within a shear layer. The Lagrangian pressure measurement technique revealed in Ref.22 and subsequently in Ref.27, rests upon the injection of a series uniform diameter air bubbles about 75 micrometers diameter into the liquid stream. These same air bubbles are observed downstream of the injection point by holography; it can be shown that mass diffusion is unimportant and that the volume of the microairbubble response sufficiently rapidly enough to reflect the true average static liquid pressure surrounding it. It was found in (27) that the static pressure extremes and rms values were considerably greater than measured with microphones.

At about the same time preliminary experiments on cavitation past a two-dimensional bluff body were reported by us in Ref.25; these clearly show that the primary effect on cavitation inception in the mixing region of such large scale shear flows is found in the axial or streamwise vortices rather than the more noticeable spanwise vortex roll-up. This was, and remains, quite astonishing to us for it shows that the "large scale coherent structure" of this turbulent flow is strong and is the feature of first importance for cavitation

inception. Now that this has been observed, we can see similar features in other cavitating mixing regions. It shows further that simplistic two-dimensional vortex roll-up models of the flow cannot account for the cavitation inception process. We have continued to pursue observations of this interesting type of generic problem for its relevance to cavitation; our tools of choice has been double-pulsed holography and the tailored airbubble technique. The object of these measurements is to learn more of the strength and structure of these streamwise 'secondary' vortices with the goal of developing simple predictive models for cavitation inception in this environment. This effort is on-going and has not yet reached a conclusive position.

Copies of contract reports and separates of publications hav been forwarded to the General Hydromechanics Research program office whenever available. It is hoped that this brief reprise and summary in the Appendix sufficiently documents the supported research.

##### 5. Acknowledgements

Many people were involved in the course of this research program whose contributions were essential and yet at the same time did not appear as authors of publications; we would like here to acknowledge the support of our loyal and hard-working staff headed up by Susan Berkley. The staff of the Keck Laboratory of Water Resources led by Mr. Elton Daly and assisted by Joe Fontana and Richard Eastvedt were also key figures in the development of new equipment and operations of the Low Turbulence Water Tunnel. To all of these people, many thanks.

Figure A3. Machine drawing of Cavitation Susceptibility Meter, top and side views. The scale of the Figure is 1:6. The numbers identify the following.

1. He-Ne Laser
2. Orientable Laser Mount (with Adjustable Location and Inclination in the Horizontal and Vertical Plane)
3. Beam Displacer (Dove Prism)
4. Micrometric Side Translation Stage
5. Beamsplitter Cube
6. First Lens of the Telescopic Relay
7. Telescopic Lens Relay
8. Second Lens of the Telescopic Relay (with Adjustable Separation)
9. Front Surface Mirror (with Slit for Transmission of the Laser Beams)
10. Longitudinal Translation Stage
11. First Cylindrical Compensating Lens
12. Second Cylindrical Compensating Lens
13. Aspheric Focusing and Collecting Lens
14. Transverse Translation Stage
15. Orientable Venturi Mount (with Adjustable Location and Inclination in the Horizontal and Vertical Plane)
16. Venturi Inlet Tube
17. Pressure Tap
18. Transparent Venturi Tube
19. Venturi Outlet Tube
20. Collimating Lens
21. Field Stop Aperture Mount (3-Dimensionally Adjustable Location)
22. Field Stop Aperture
23. Photomultiplier

C.S.M. OPTICAL SET-UP

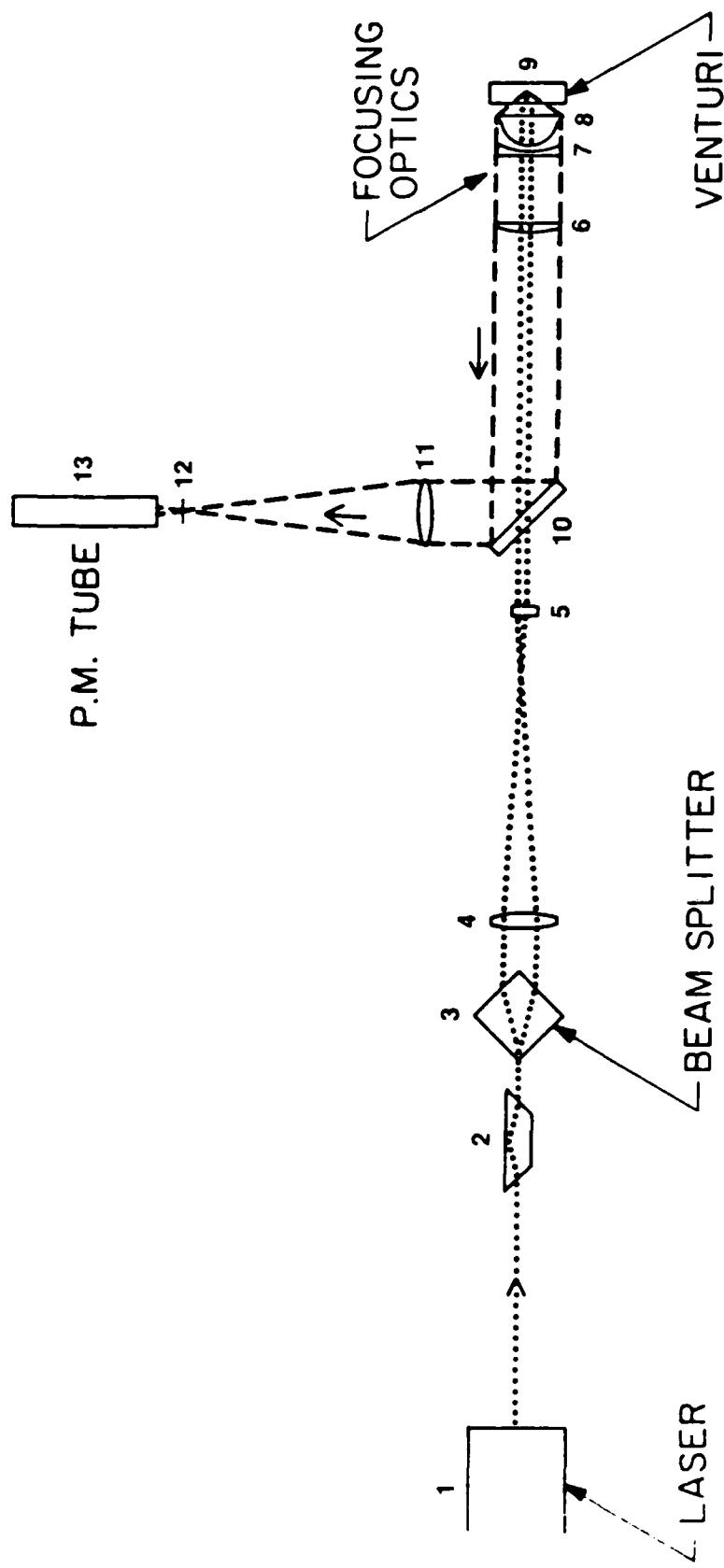


Figure A2

Figure A2. Optical design of the Cavitation Susceptibility Meter. The beam separation and the cylindrical lens corrector assembly are all adjustable. It will be noticed that a back-scatter system is used with an aspheric lens of focal ratio  $f/ \# = .62$  to focus and collect the scattered light from the venturi. The adjustable optical feature permits operation over a wide Doppler frequency range. The numbers refer to the components below:

1. He-Ne Laser
2. Beam Displacer (Dove Prism)
3. Beamsplitter Cube
4. First Lens of Telescopic Relay
5. Second Lens of Telescopic Relay
6. First Cylindrical Correcting Lens
7. Second Cylindrical Correcting Lens
8. Aspheric Focusing and Collecting Lens
9. Transparent Venturi Tube
10. Front Surface Mirror (with Slit for Transmission of Laser Beams)
11. Photomultiplier Collimating Lens
12. Photomultiplier Field Stop Aperture
13. Photomultiplier Tube

C.S.M. SET-UP SCHEMATICS

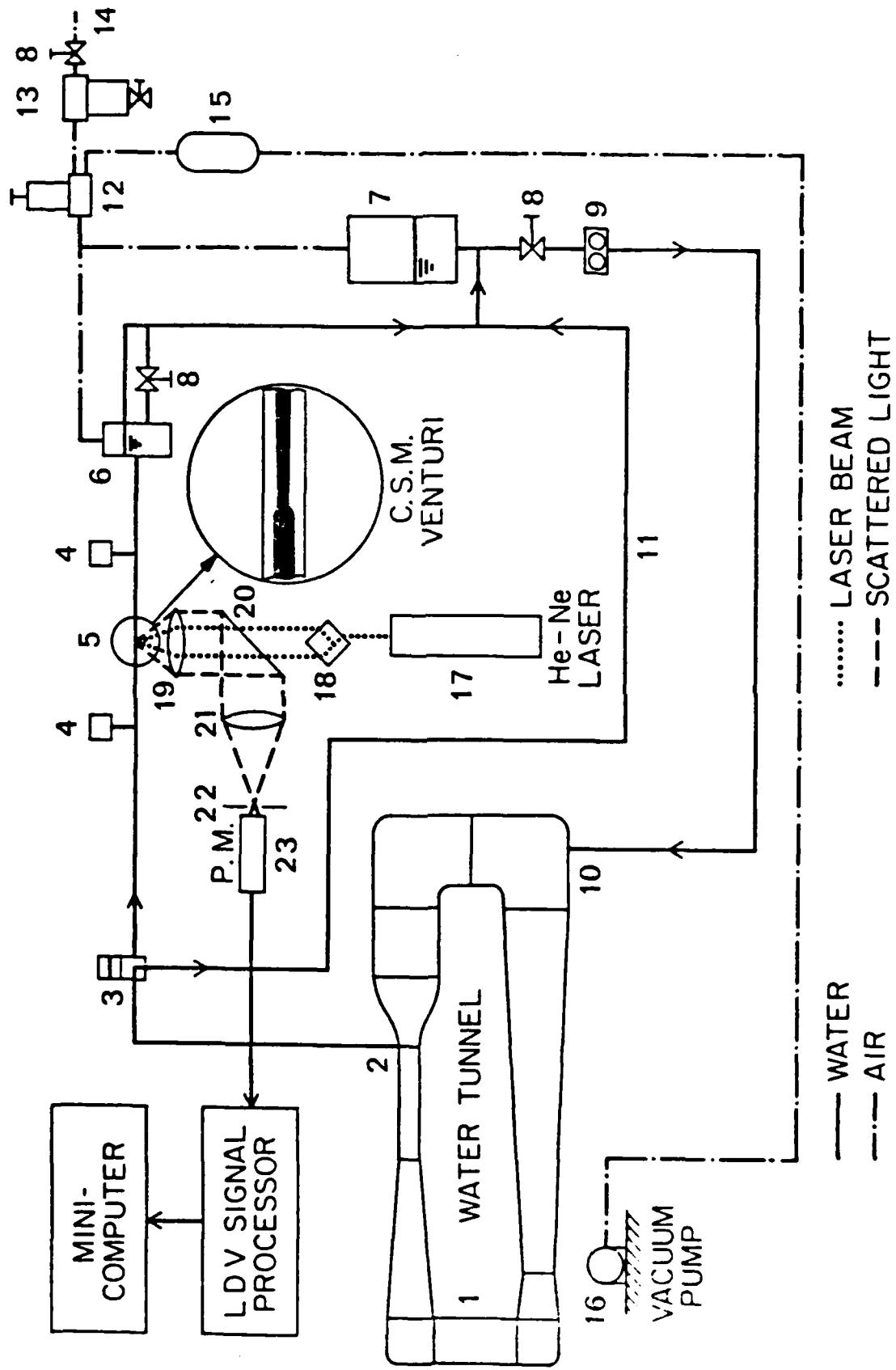


Figure A1

**Figure A1. C.S.M. Set-up Schematics**

1. Water Tunnel
2. Water Sampling (from Water Tunnel)
3. Three Way Valve
4. Pressure Transducer
5. Transparent Venturi Tube
6. Water/Vapor Separator
7. Pressure Regulated Discharge Tank
8. Valve
9. Water Pump
10. Water Return (to Water Tunnel)
11. C.S.M. By-pass Line
12. Back-Pressure Regulator
13. Air Filter
14. Air Inlet (atmospheric)
15. Vacuum Reservoir
16. Vacuum Pump
17. He-Ne Laser
18. Beamsplitter
19. Focusing and Collecting Optics
20. Front Surface Mirror (with Slit for Transmission of Laser Beams)
21. Collimating Lens
22. Field Stop Aperture
23. Photomultiplier

and  $S_1$  are zero and reset to a low value by the next zero crossing. Finally, the gate time signal,  $S_g$ , is set to a high value by the first validated zero crossing and reset to a low value by the first zero crossing for which  $S_f$  is at the high value. The gate time signal is used together with the validated zero crossing signal to measure the LDV Doppler frequency. Additional checks are also made to insure that a sufficient number of validated zero crossings have been counted for accurate frequency measurement.

threshold levels by the bubble/particle discriminator to recognize the presence of either a velocity tracer (particle), a cavitation bubble, or an undetermined scatterer. The output of the second amplification stage is high-pass filtered (or band-pass filtered, if necessary for noise reduction) to separate the Doppler modulated signal, whose frequency is measured by the frequency counter. Additional time and cavitation event (bubble) counters with adjustable maximum capacity provide information on the time history of the run and the stop signals for its conclusion. The collected data, including the upstream pressure measurements, are temporarily stored in a non-permanent memory and finally transferred by an interface to a computer after the end of each run for recording and further reduction. The flux of information among the various parts of the system during each run is regulated by a control unit.

Due to the different intensity and duration of the LDV signal and to the presence of noise from various sources, the frequency counter incorporates logic devices for signal validation, according to a scheme very similar to the one described by Durst, Melling & Whitelaw. The high-pass filtered LDV signal is compared with the upper, zero and lower levels and the resulting signals are logically combined to generate five pulse trains,  $S_u$ ,  $S_1$ ,  $S_0$ ,  $S_f$  and  $S_g$ , as shown in Fig. 5. The first signal,  $S_u$ , is set to a high value by the upper level crossing and reset to a low value by the next zero crossing. Similarly, the second signal,  $S_1$ , is set to a high value by the lower level crossing and reset to a low value by the following zero crossing. The third signal,  $S_0$ , is changed of polarity at any zero crossing for which either  $S_u$  or  $S_1$  is at the high value, therefore yielding a validated zero crossing signal. The signal  $S_f$  (a flag) is set to a high value by the first zero crossing for which both  $S_u$

correction relay is also adjustable in order to insure both perfect parallelism of the emerging beams and optimal compensation of the cylindrical distortion. The C.S.M. blown glass venturi is contained in a protective cylindrical shell of cast transparent resin for connection to the hydraulic lines (16 & 19) and easy installation and removal. It is also mounted on a transverse translation stage to allow the measurement of the flow velocity along its centerline. In addition, the C.S.M. test section (18) can be finely positioned and oriented in both the horizontal and vertical planes for accurate location at the focal point of the optical system. Pressure taps (17) are located in the water inlet and outlet of the test section. Finally, the photomultiplier field stop aperture (22) can also be accurately positioned in space for optimal reduction of the optical background noise.

#### Signal Processor

The signal processor is used for real time collection, temporary storage and subsequent transfer to the computer of the data obtained from a C.S.M. run, namely: the total number of cavitation events, the occurrence time of each of them and the corresponding throat velocity and upstream pressure of the water. The flow velocity is deduced from the Doppler modulated frequency; the occurrence of cavitation from the intensity pedestal of the photomultiplier signal; the instantaneous upstream pressure of the water from the output of a pressure transducer.

A simplified block diagram of the LDV part of signal processor is shown in Fig. 4. After pre-amplification, the output of the photomultiplier is sent to both a low pass-filter for pedestal separation and to a second amplification stage. The signal pedestal is then used with reference to two adjustable

by a 5 mw He-Ne laser (1), goes through a beam displacer (dove prism) (2) and a metal-coated beamsplitter cube (3). The separation of the two emergent beams can be widely adjusted by changing the transverse position of the beam entering the beamsplitter. In order to reduce the Doppler frequency of the LDV signal and consequently simplify the processing electronics, the beam separation is then reduced by a factor of 4 with the telescopic relay (4 & 5). After passing through a slit in the front surface mirror (10), the two beams are corrected for cylindrical distortions due to the venturi tube in a cylindrical lens relay (6 & 7) and are finally focused by a fast aspheric lens (8) in the test section of the C.S.M. venturi tube (9). The back-scattered light, also collected by the aspheric lens with the highest possible aperture in order to maximize the signal to noise ratio, is once again corrected for cylindrical distortion and mostly reflected by the front surface mirror (10) towards the photomultiplier collimating lens (11). The resulting image of the test section is filtered by a field stop aperture (12) to reduce the optical background noise and finally reaches the photomultiplier tube (13) where is converted into an electric signal.

The actual C.S.M. optical lay-out is shown in Fig. A3, with the plan view at the top of the picture and the side view at the bottom. Two I-beams in a T-shape configuration support both the laser (1) and the base-plate, where all the other optical components are installed. The laser mount (2) allows fine positioning and orientation of the laser in both the horizontal and vertical planes. The beam displacer (3) is mounted on a micrometric lateral translation stage (4) for repeatable and accurate control of the separation of the two beams emerging from the beamsplitter (5). The distance between the two lenses (6 & 8, 11 & 12) of both the telescopic relay (7) and of the cylindrical

### Cavitation Susceptibility Meter (CSM) Arrangements

The C.S.M. currently under development at Caltech is meant to be used for testing of any water source with pressure in the range 0 to 2 bar. A typical application of the C.S.M. to the measurement of water quality in the C.I.T. LTWT is schematically shown as an example in Fig. 1. Different configurations are of course possible with other water sources.

The water, sampled near the water tunnel test section (2), passes through a three-way valve (3) which operates either the by-pass line (11) or the C.S.M. testing line. The water static pressure is monitored by a pressure transducer upstream of the test venturi tube (4). Provisions have been made for the installation of a second pressure transducer downstream of the C.S.M. test section to monitor also the exhaust pressure, if necessary. The flow velocity at the throat of the transparent venturi (5) is measured by a dual beam back-scattering LDV system, described later. Operation with flooded or non-flooded venturi exhaust can be obtained by proper selection of the water drain line from the water/vapor separator (6) downstream of the test section. The water is then collected in the large pressure regulated vessel (7) and finally returned after every run to the water tunnel by means of a small pump (9). The pressure regulation line originates from a 0 to 20 psia back-pressure regulator (12) connected through a filter (13) to the atmosphere (or to a compressed air supply (14), if necessary) and to a vacuum pump (16) through a vacuum reservoir (15).

### C.S.M. Optical Set-Up

The C.S.M. optical set-up consists of a dual beam back-scattering LDV system, whose optical elements are shown in Fig. A2. The laser beam, generated

## **Appendix 2**

**Design of the Cavitation Susceptibility Meter**  
**(Refer to Reference 24 for the design computations)**

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## Appendix 1

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**Appendix 1**

**Publications and reports supported all or in part  
under the present contract**

Figure A3

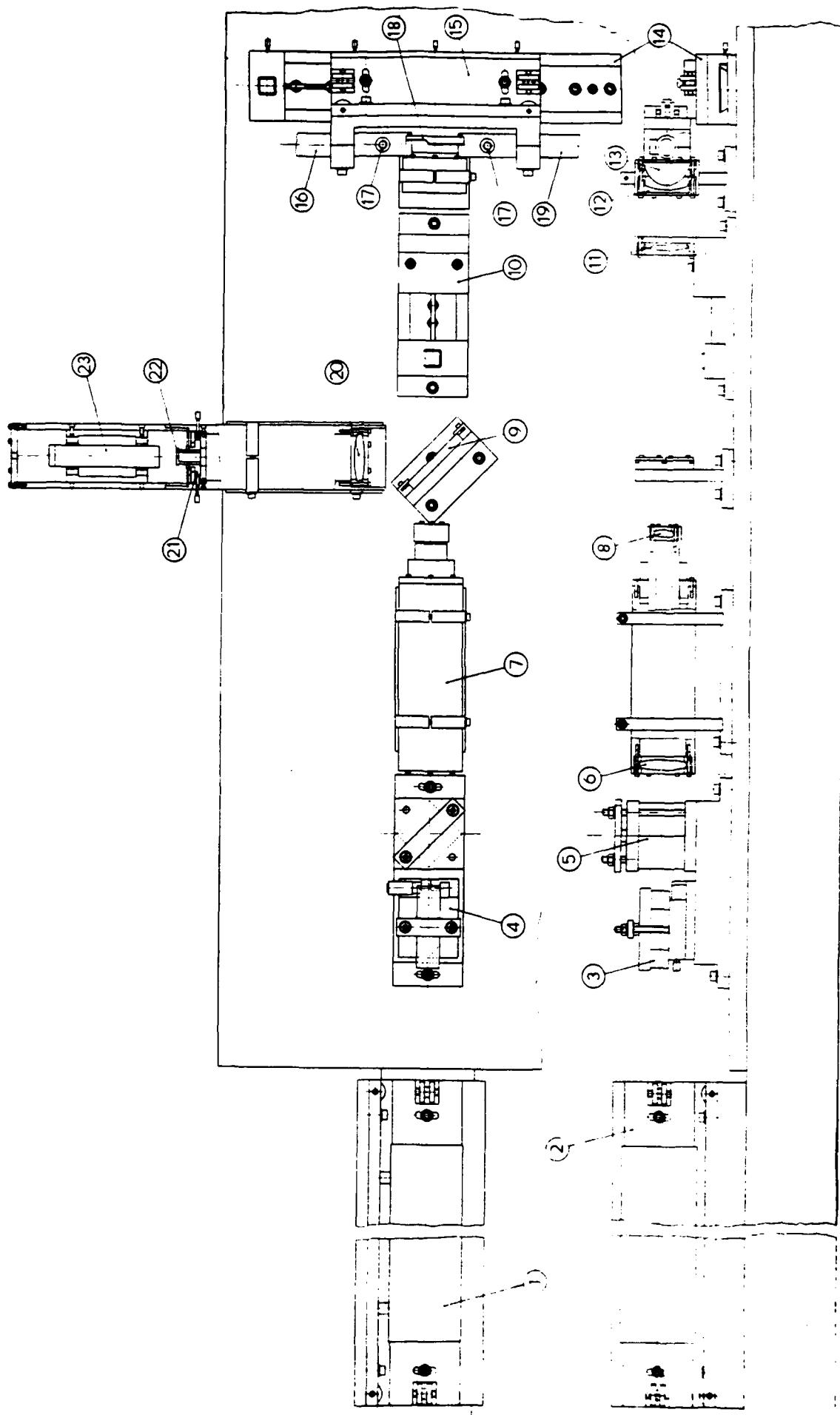


Figure A4. Block diagram of information flow for the Cavitation Susceptibility Meter processor. The high low frequencies are adjustable as is the bubble/particle discriminator levels. The number of bubble counts and run time are variable as is the minimum number of validated zero crossings for Doppler frequency measurement. These components are all contained in the Shaprio Scientific Inst. processor; still to come is the interface and microcomputer.

# LDV SIGNAL PROCESSOR BLOCK DIAGRAM

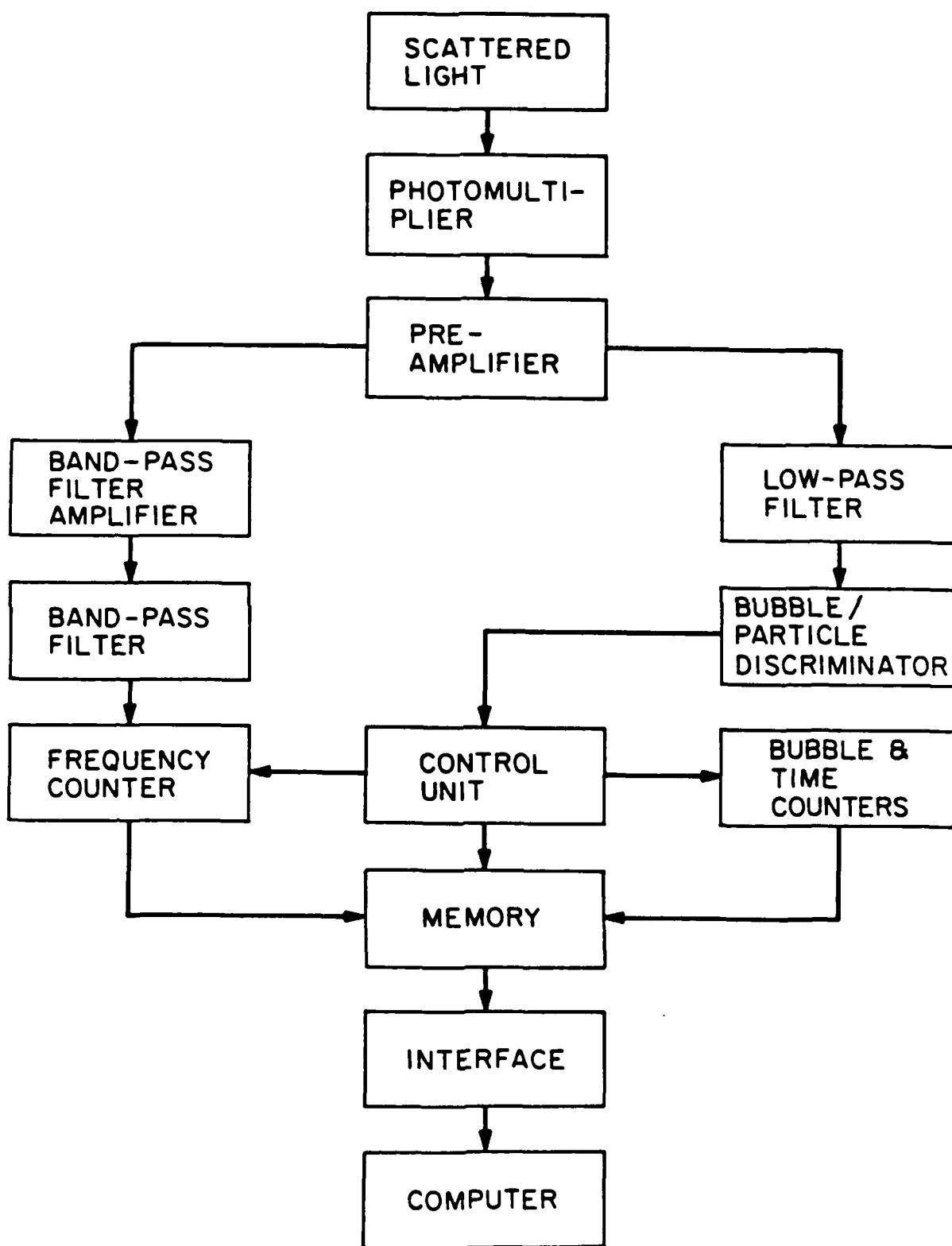
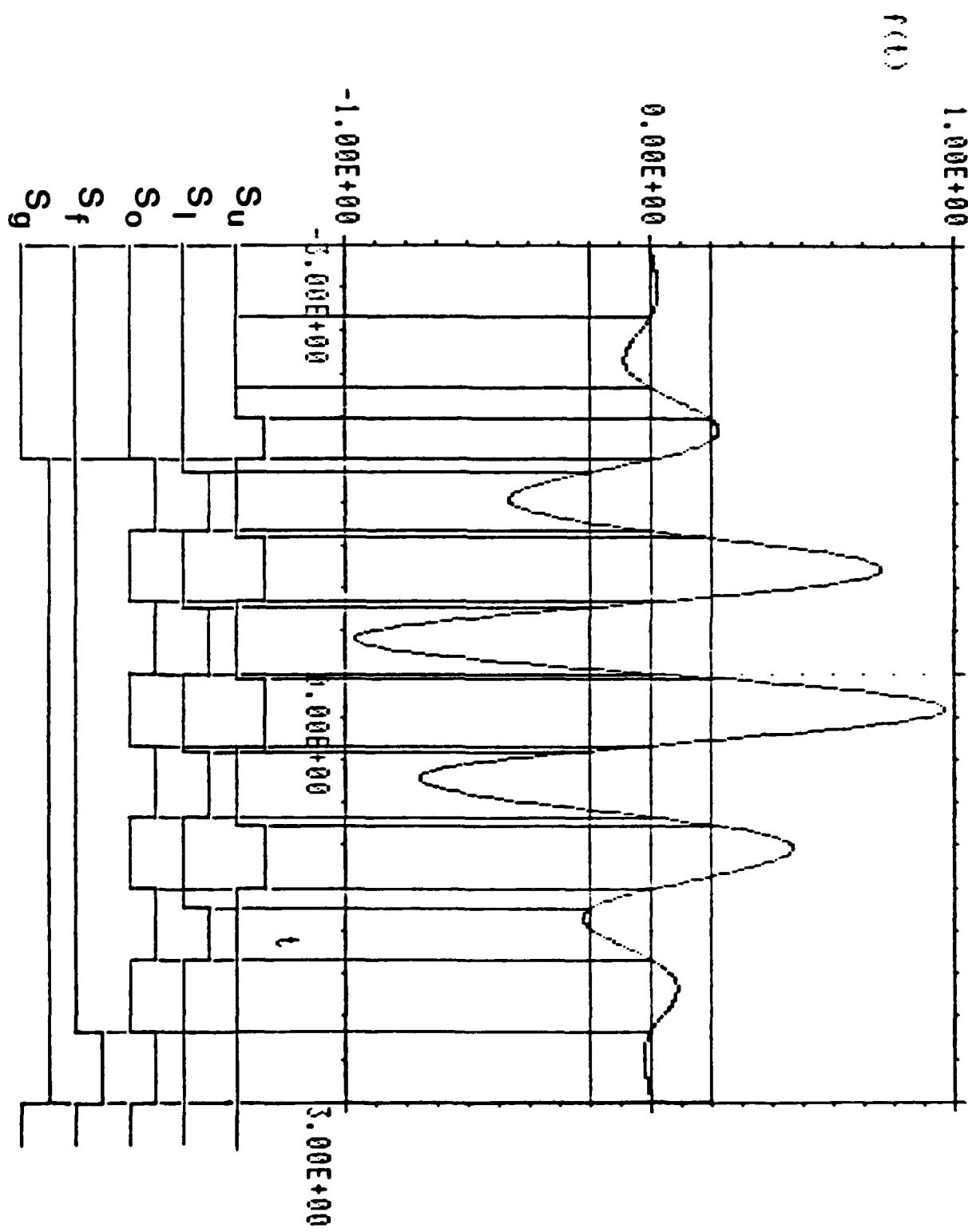


Figure A5. Level crossing logics for noise rejection and Doppler frequency validation from high-passed LDV signal. Generated signals:  $S_u$ , upper level crossing;  $S_l$ , lower level crossing;  $S_0$ , zero crossing;  $S_f$ , auxiliary signal for burst termination detection;  $S_g$ , gate time (burst duration) signal.

Figure A5



**END**

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